Real-Time Measurements of Sediment Modification by Large Macrofauna

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LONG-TERM GOALS

Marine sedimentary infauna alter acoustic properties of sediments by creating voids and air bubbles, manipulating grain and shell distributions, moving interstitial fluid and creating surface roughness elements. Our prior results from ONR support suggest that conceptual models of organism modifications of solute flux are grossly inaccurate in both diffusion-dominated and advectively permeable environments. The porewater transients detected by our pressure transducers represent several cm of water pressure in many cases and result in advective flows. The strong, pulsed flows imposed by organisms are radically different from the current models of irrigation-mediated transport or surface-driven porewater advection, a result with significant implications for bacterial transformations and particle movements. Our research addresses fundamental questions in benthic biological oceanography with significant relevance to naval operations: what factors affect infaunal activity patterns and movements and how do these processes affect sediment acoustic properties? Our research has three thrusts: (1) the development of new technologies to measure, in real-time, organism movements and the effects of these movements on the pressures, voids, fluid flows and surface roughness elements of nearshore sediments; (2) the experimental determination of the ecological and geochemical factors, including organism density, resource availability, and the concentration of metabolites in porewater that affect rates of organism movement; and (3) the evaluation of the ecological and geochemical consequences of these interactions. These results will allow us to link the behaviors and dynamics of macrofauna to ecosystem-level processes in coastal habitats and to the predictability of acoustic properties of operational importance to the Navy.

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OBJECTIVES

This proposal is centered on expanding (1) our sensor capabilities to allow remote detection of organism activities in sediments utilizing porewater pressure transients, vibrations and optical methods; (2) the number of species, water depths and types of sedimentary environments within our database; and (3) the linkages of organisms' activities to alteration of the acoustical, geochemical, and biotic properties of sediments.

The research also fulfills three important goals within ONR's Biological and Chemical Oceanography Program: (1) to enable the prediction of the distribution and abundance of biota and their interactions with biogeochemical processes in shallow water sediments, (2) to understand how biota affect the acoustical properties of operational importance to the Navy, and (3) to explore new instruments to sample and observe biological processes.

APPROACH

Our experimental approach is centered on the supposition that relocation of individuals and biogenic modification of the physical and chemical matrix are driven by interactions among organisms and their biological and geochemical environment. Our experimental approach, in combination with new technologies, has provided a mechanistic understanding of organism-sediment interactions that highlights the importance of ecological processes in sediments and has broad scale significance for coastal processes. We are particularly interested in species that are widely distributed, common and large such as *Arenicola marina* along the European coast, *Abarenicola pacific* in the northern Pacific, and a variety of tellinid bivalves. We are focusing on related species where we can ask whether similar behaviors by comparable body forms result in predictable signals and associated sediment alterations. We are particularly interested in *Arenicola marina* both as a comparison to *Abarenicola pacifica* and because of the extensive literature on its impacts.

Our initial research confirmed that pressure sensors could detect infaunal activities in unrestrained individuals in the field and that we could differentiate among activities and species (Wethey and Woodin 2005). We developed differential pressure transducers which allow deployment at greater depth, have greater sensitivity and are small, allowing us to deploy them in two-dimensional arrays.

Progress in the Marinelli lab has focused on technique development and synthesis of data from previous experiments that reveal additional complexities concerning organism-sediment-flow interactions. Senior graduate student Waldbusser is leading some of the technology development. The overall goal is to develop technologies that allow us to capture sediment heterogeneities in a more dynamic mode, to link specific organism activities to physical and biogeochemial properties and to examine the spatial and temporal dependence of these processes. To this end we are using a spectrofluorometer with a fiber optic sensor for exploration of surface detrital flux to depth in sediments plus benthic surface fluorescence mapping techniques, using excitation and barrier filters on a digital camera. Both of these approaches add a comparative element to the optode technologies discussed below and provide a different spatial and temporal scale of observation that can be used in longer term experiments.

Laboratory experiments allow a mechanistic view of how infauna interact with physical and biogeochemical properties of sediments. Experiments by Waldbusser have focused on the role of advection rate: how do different rates of porewater advection affect the biogeochemical signal imparted by infauna? These experiments help place our laboratory measurements in a broad environmental context.

Planar optode technology in combination with our pressure sensors and video techniques has the potential to yield information on nutrient fluxes driven by pressure pulses due to organism behaviors. Nils Volkenborn (Alfred Wegener Institute for Polar and Marine Research) and Lubos Polerecky (Microsensors Group, Max Planck Institute for Marine Microbiology) are collaborating with us on using oxygen optodes to explore the effect of pumping by *Arenicola marina* on nutrient flux in sediments differing in permeability. In addition, Dr. Michael Angel, a developer of multilayer optodes, has begun development of optodes with multiple sensitivities. We are particularly interested in optodes with sensitivities for both oxygen and ammonium.

Our field measurements of advective forces associated with activities of large abundant infauna are used to confirm the laboratory data. We are using areas from which large infauna have been excluded so that the biogenic hydraulic head causing advection can be measured. Nils Volkenborn and Karsten Reise (Alfred Wegener Institute for Polar and Marine Research) have allowed us to use their long term exclusion experiments (20 m by 20 m) involving large arenicolid polychaetes at Sylt Germany and we have developed a continuing collaboration. All of these results will have strong implications for physical-chemical biological coupling in the coastal ocean and the degree to which it is pulsile, local and density dependent.

WORK COMPLETED

- We have pressure and video recordings of two arenicolid polychaetes. *Abarenicola pacifica* is abundant from northern California to Japan while *Arenicola marina* is often the infaunal dominant on the coast of Europe. Similar behaviors by the two species result in similar pressure waveforms.

- In *Arenicola marina*, we have measured the advective forces associated with behaviors in the field and have mapped those forces using a combination of modeling and pressure sensors.

- We have successfully deployed our differential pressure sensors in the field.

- We have concluded that due to the forces involved and the absence of differential accelerometers with the necessary sensitivity that we will be unable to detect biotic driven transients on the accelerometers.

- We have completed several sets of complementary experiments to investigate nonlinearities in the magnitude of sediment-seawater exchange rates as a function of density and activity of infauna.

- We have expanded our use of pressure sensors to several common tellinid bivalves and some behaviors such as burrowing look strikingly similar while others do not. We are analyzing data for a third tellinid.

- We have calibrated the spectrofluorometer with its chlorophyll sensor and find a reasonable relationship between the output signal and direct measures of chlorophyll fluorescence. These measurements include calibration solutions as well as in situ measurements.

- Benthic chlorophyll mapping techniques have been successfully developed.

- Experiments testing the role of advection relative to infauna have been completed.

- Experiments testing the role of density dependence and food on biogeochemistry have been reanalyzed to reveal larger scale temporal differences in our earlier findings.

- Using a combination of oxygen planar optodes, video, ultrasound, and pressure sensors we have shown how porewater exchange changes as a function of hydraulic activities of *Arenicola marina* and the degree to which this is influenced by differences in sediment permeability.

RESULTS

A major thrust of this project was to ask whether calculations of the sphere of influence of large hydraulically active individuals such as *Arenicola marina* was restricted to the area directly in contact with the individual and its burrow. Without knowledge of the lateral impact on sediment properties one cannot estimate the importance of biota as drivers of sediment properties or assemblages. We have now shown that the radius of spheres of influence in the field is often 50cm. We predicted this with numerical models and now have verified those model results with field measurements (Fig. 1C and D). We presented these results at ASLO 2007.

The results of our modeling and our measurements of pressure transients indicated that the direction of advective force changed as arenicolid polychaetes switched from pumping from tail to head, the usual direction of activity, and pumped from head to tail, an activity associated with burrowing. Tail to head pumping *increases* porewater pressure causing porewater to flow laterally and vertically away from the burrow (Fig. 1C and D). Head to tail pumping *decreases* porewater pressure as evidenced by reduction in baseline pressures in our measurements and could result in entry of oxygenated water into sediments across wide areas of sediment surface. These effects would be expected to change as a function of sediment permeability which affects the distances over which porewater pressures are altered by animal activities. To explore this we established a collaboration with Lubos Polerecky at the Max Planck Institute for Marine Microbiology and Nils Volkenborn at the Alfred Wegener Institute for Polar and Marine Research. We combined geochemistry, physics, and behavior studies of *Arenicola marina* using simultaneous pressure sensor data, time lapse imagery, and planar oxygen optode imagery. In Fig. 1A, the animal is pumping surface water down the vertical tail shaft of the burrow near the left side of the image, causing an increase in oxygen concentration around the burrow in the deep areas of the sediment, and causing multiple plumes of anoxic porewater (blue/purple) to flow out of the sediment-water interface. In Fig. 1B, oxygentated water pumped down the tail shaft is percolating through a large area of the quicksand feeding column on the right of the image. Parts C and D of Figure 1 depict modeled porewater velocity contours and porewater trajectories from the feeding pocket of the animal.

To ask whether pressure transients produced by common tellinid bivalves were associated with similar behaviors we recorded activities in the laboratory and in the field in North America (*Macoma nasuta*) and New Zealand (*Macomona lilana*). Both species are important members of their assemblages. The pressure transients for burrowing look similar across species (Fig. 2) but unlike in the arenicolids, differences in waveform are apparent. A behavior that should be important in altering sediment properties is the movement of the siphon from one location to another in that it involves a strong positive pressure transient produced by the animal pumping water out of the siphon as it moves through the sediment. This is common in *Macoma nasuta* but we have yet to see this pressure transient in *Macomona lilana* although it does relocate its siphon. Burrowing similarly involves major disruptions of sediment grains and porewater and both species show the associated pressure transients.

Simon Thrush and Judi Hewett at NIWA in New Zealand are engaged in a very large project on the effect of terrigenous sediment deposition on infauna assemblages and sediment properties of coastal habitats. We established a collaboration with them to ask how behaviors and resulting geochemical flux might be altered given a gradient of deposition. The behavioral changes in a tellinid bivalve were dramatic with a significant increase in both violent mantle cavity clearances and in burrowing.

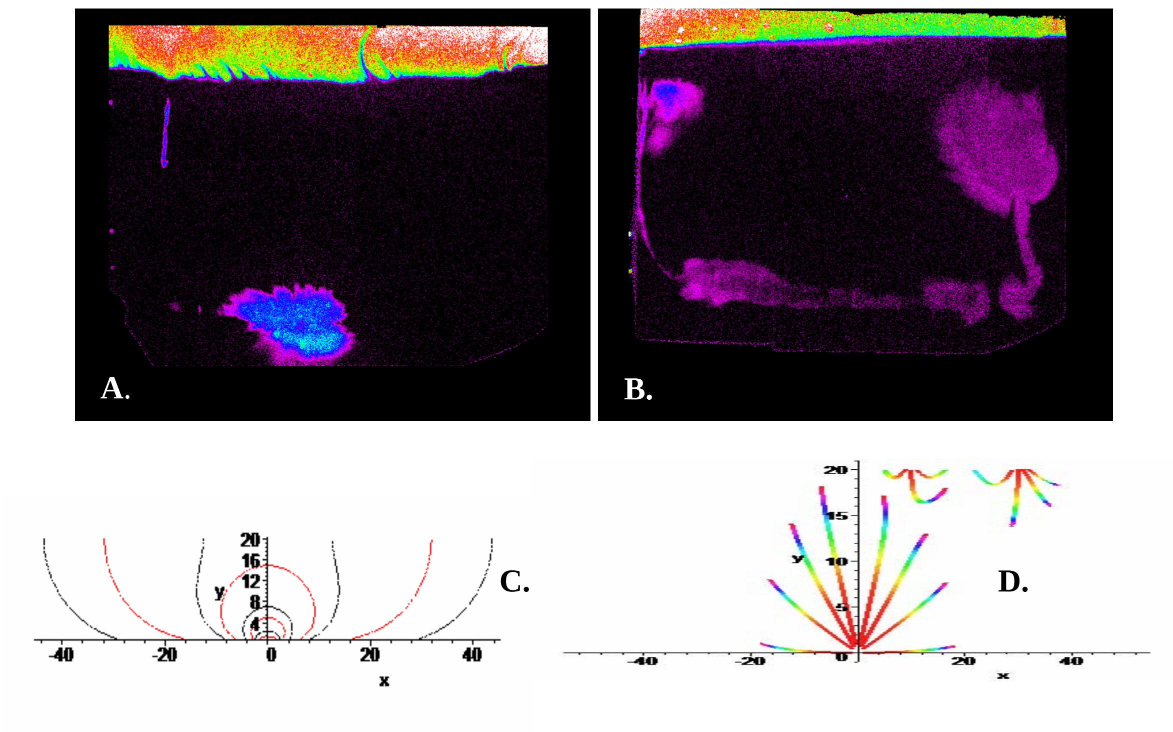

Figure 1. A. and B. Oxygen optode images showing result of tail to head pumping in Arenicola marina. In part A. in muddy sands of relatively high permeability, such activities result in multiple plumes of anoxic porewater (blue/purple) emerging from the sediment surface. In part B, the oxygenated water pumped down the tailshaft on the left side of the image percolates through a large area of the head shaft on the right side of the image. Brighter colors correspond to higher oxygen concentrations in the image. In part C. are model porewater velocity contours (10, 1, 0.1, 0.01 cm d^{-1}, black is outward flow during ventilation, red is inward flow during defecation). Part D. shows 24-hr trajectories of porewater from the feeding pocket and from the feeding pit and fecal mounds on the sediment surface (red zone is trajectory over 1 h, purple is endpoint at 24 h). In both C. and D. the origin is centered on the feeding pocket of the animal.

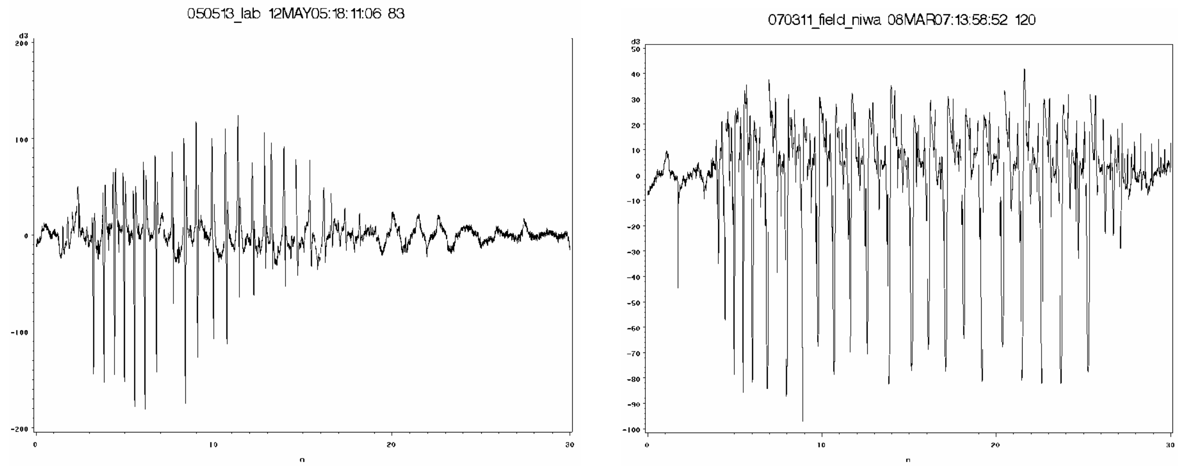

Figure 2. Burrowing signals of Macoma nasuta (left) and Macomona lilana (right). Porewater pressure (Pa). Both species generate large negative and positive porewater transients.

Our early laboratory results suggested that intermediate densities of *Abarenicola pacifica* produced, on average, higher fluxes than control (zero) or high densities, as defined by the *Abarenicola* community resident at False Bay in Washington State. We concluded that biogeochemical properties do not scale monotonically with typical measures of organism activity and that organism-environment interactions were responsible for the observed trends. In addition, growth of organisms in our first set of experiments exhibited positive density dependence, i.e. greater growth occurred under more crowded conditions, likely the result of infaunally-enhanced rates of benthic primary production.

The advection experiments suggest that infauna have marked effects on biogeochemical properties and sediment-seawater exchange rates at relatively slow rates of advection. At higher flow rates, infaunal effects are erased. However, field measurements suggest that in highly productive muddy sands, low rates of advection are common and infaunal manipulation of the physical and chemical sediment properties are significant. Calculations suggest that infaunal effects can impact water column chemistry, particularly with regard to elemental ratios. These results were presented at ASLO 2007.

IMPACT/APPLICATIONS

Our data consistently demonstrate the pulsile nature of infaunal advective forces in sediments. They also strongly support the idea of positive synergistic interactions (Allee effects) among conveyor-belt feeders such as arenicolid polychaetes. This is consistent with observed patchy spatial distributions and implies non-random but predictable differential rates of sediment movement, remineralization, and bacterial activity.

RELATED PROJECTS

The work of Peter Jumars on sediment cracking by infauna and alterations of sediment textures by such activities is clearly related. We have been conversing with one another and we have provided him with video footage of sediment cracking by arenicolid polychaetes. The models of Bernard Boudreau require measurements of advective forces by organisms. We will be able to provide him with these from measurements such as those at Sylt across a known density boundary of organisms.

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